ANALYSIS OF PROCESS PARAMETERS OF PLASMA ARC CUTTING USING DESIGN OF EXPERIMENT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

FOR THE REQUIREMENT FOR THE DEGREE OF

Master of Technology

In

Production Engineering

By

VIVEK SINGH

Department of Mechanical Engineering

National Institute of Technology

Rourkela

2011

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Under the guidance of

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CERTIFICATE

This is to certify that the thesis entitled, "ANALYSIS OF PROCESS PARAMETERS OF PLASMA ARC CUTTING BY USING DESIGN OF EXPERIMENT " submitted by Vivek Singh (207ME209) in partial fulfilment of the requirements for the award of Master of Technology Degree in Mechanical Engineering with specialization in Production Engineering at the National Institute of Technology, Rourkela (deemed University) is an authentic work carried out by him under my guidance.

To the best of my knowledge, the matter embodied in the thesis has not submitted to any other University/Institute for the award of any degree or diploma.

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207ME209

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ABSTRACT

In last forty years there is tremendous research in machining and development in technology. With increase in competition in market and to attain high accuracy now a days the nonconventional machining are become lifeline of any industry. One of the most important non conventional machining methods is Plasma Arc Machining. Its high accuracy, finishing, ability of machining any hard materials and to produce intricate shape increases its demand in market.

In thesis work literature has been studied in context to parametric optimization of Plasma Arc Cutting Machine. In order to attain target and optimum results, Taguchi method employed. The appropriate orthogonal array has been selected as per number of factors and there levels to perform minimum experimentation.

The work pieces of Stainless Steel (316 L) materials were used for experiment purpose. The optimum value has been determined with the help of main effect plot and ANOVA table. The Regression equation for MRR and Surface Roughness (Ra) has been developed with the help of Minitab 15 Software. Confirmation test have done to confirm the value estimated through the software.

The Confirmation for MRR run was done by using the setting of 5.0 bar (Gas pressure), 150 A (Current flow rate), 600 mm/min (cutting speed) and 4.0 mm (arc gap). The optimum parameter level for Surface Roughness are 6.0 Bar (Gas Pressure), 150 A (Current), 400 mm/min (Cutting Speed) and 2 mm (Arc Gap). Experimental results are provided to confirm the effectiveness of this approach. After the confirmation the MRR value was 0.8331 g/sec and Ra 2.635µm. Error within 10 % was allowed.

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 OVERVIEW

The topic for the thesis writing is the Analysis of Process Parameters of Plasma Arc Cutting Using Design of Experiment Techniques. The focus on this project is to obtain an optimum condition (setting) to obtain maximum MRR and minimum the surface roughness (SR).

A person doesn't need to be a physicist or chemist to understand the Plasma Arc Cutting (PAC) and Gouging process. There are four states in which physical matter may be found: solid, liquid, gas or plasma. Changes from one physical state to another occur, by either supplying or subtracting energy, in the form of heat.

Water can be used as an example of these four states of matter. In the solid state it is ice at temperatures of 0 degrees Celsius or colder. With the addition of heat the ice melts and changes to water, the liquid state. The addition of more heat to temperatures of 212 degrees F. (100 degrees C.) or hotter) converts this liquid to its gaseous state, steam.

The fourth state of matter, plasma, looks and behaves like a high temperature gas, but with an important difference; it conducts electricity. The plasma arc is the result of the electrical arcs heating of any gas to a very high temperature so that its atoms are ionized (an electrically charged gas due to an unequal number of electrons to protons) and enabling it to conduct electricity. The major difference between a neutral gas and plasma is that the particles in plasma can exert electromagnetic forces on one another.

If you happen to be reading this by the light emitted by a fluorescent lamp you see plasma in action. Within the glowing tube of the lamp is plasma consisting of low pressure mercury or sodium vapour. It is ionized by a high voltage across electrodes at the ends of the tube and conducts an electric current which causes the plasma to radiate which in turn causes the phosphor coating on the inner surface of the tube to glow [19] .

For many years, oxy-acetylene cutting was often the process of choice for quickly cutting through steel plate. Over the past few years plasma cutting has pretty much taken over, for some very good reasons to perhaps most importantly. A plasma cutter will cut through any metal that is electrically conductive. That means that one unit will cut steel, stainless steel, aluminium, copper, bronze, and brass etc.

The plasma jet that does the cutting is hotter and narrower than an oxy-acetylene flame, so the kerfs width is smaller, and can get cleaner cuts. This makes plasma cutting particularly well-suited for cutting sheet metal, a task the oxy-acetylene cutting torch is not particularly well-suited for since it leaves a lot of slag on the edges. The extremely tight focus of the plasma arc tends to minimize heat distortion in the cut parts, as well.

1.2 PROCESS DESCRIPTION

Plasma cutting is a process that is used to cut steel and other metals (or sometimes other materials) using a plasma torch. In this process, an inert gas (in some units, compressed air) is blown at high speed out of a nozzle, at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is sufficiently hot to melt the metal being cut and moves sufficiently fast to blow molten metal away from the cut. Plasma can also be used for plasma arc welding and other applications [24].

FIG. 1.1 PAC Arc Cut-Away

The plasma arc torch has a space or area surrounding the circumference of the electrode, between the inside circumference of the torch tip or nozzle. It is in this chamber that the plasma gas is heated and ionized. This heating causes the plasma gas to greatly expand in volume and pressure. The plasma gas exits from the constricting orifice of the torch nozzle or tip at very high speeds and temperatures; up to 30,000 degrees F. (16,000 degrees C.) and 6000 m/s (20,000 ft/s). The intensity and velocity of the plasma is determined by several variables including the type of gas, its pressure & volume, the flow pattern, the amount of electric current, the size and shape of the constricting tip or nozzle orifice, and the tip to work distance.

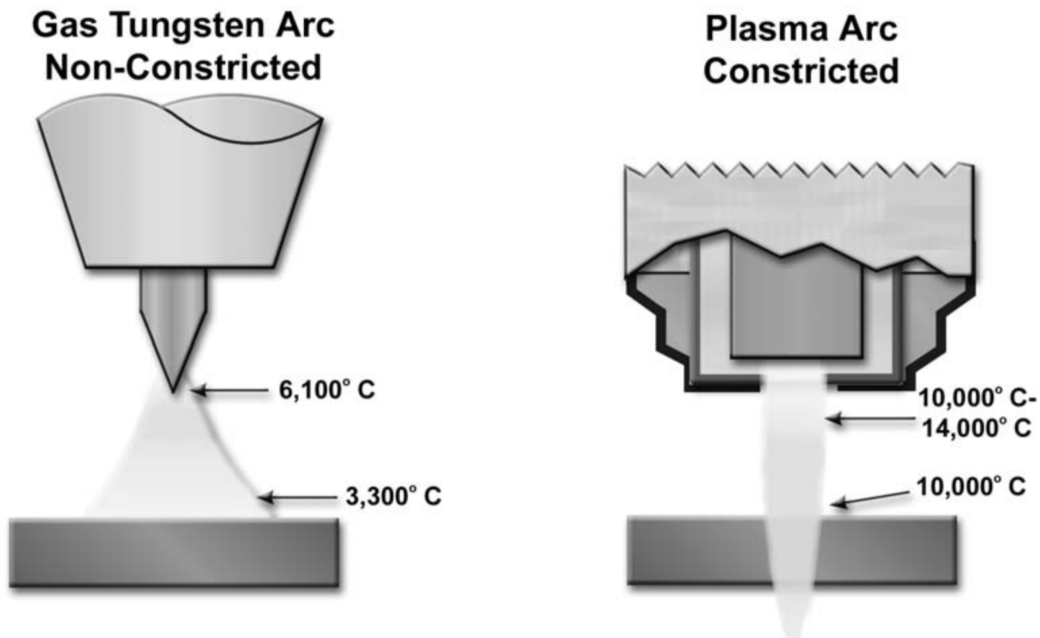


FIG. 1.2 TIG and Plasma Arcs

The PAC process uses this high temperature, constricted, high velocity jet of ionized gas exiting from the constricting orifice of the torch tip to melt a much localized area and remove the molten material from the metal being cut by the force of the plasma jet. The force of the arc pushes the molten metal through the work piece and severs the material. Extremely clean and accurate cuts are possible with PAC. Because of the tightly focused heat energy, there's very little warping, even when cutting thin gauge sheet metal thickness. PAC also offers quality gouging and piercing capabilities [17].

1.3 INTRODUCTION TO PROBLEM

Advanced materials exhibit very excellent technical properties. However, the high cost of both raw materials and processing limit their use. Alternatively, advanced machining such as Plasma Arc Cutting is normally used. Advanced material such as nickel-base alloys, titanium alloys and stainless steel can be used as the work piece in this type of cutting.

A torch in which temperatures as high as 30,000°C are achieved by injecting a plasma gas tangentially into an electric arc formed between electrodes in a chamber; the resulting vortex of hot gases emerges at very high speed through a hole in the negative electrode, to form a jet for welding, spraying of molten metal, and cutting of hard rock or hard metals [25].

The plasma arc also cuts ferrous and non-ferrous metals much faster than an Oxy-Fuel torch or abrasive saws, with low or no heat affected zone, especially on thinner metals. A clean cut with little or no dross means less time and money is required to finish the work piece. Parts are virtually weld-ready.

With plasma cutting, less preparation work is required. A plasma arc is hot enough to burn through most surface coatings such as paint and rust and still provides excellent cutting results. With plasma cutting, there is minimal heat input and distortion of the metal as there is with jigsaws or cutting shears. For applications where difficult shapes are being handled or cut, such as ventilation ductwork (HVAC), tanks or vessels, plasma cutting offers considerable advantage since no fixturing is required [25].

The feasibility and effectiveness needs to be proven by experiment and by using Taguchi Method of the processing parameter to obtain the best factors combination (MRR and Surface Roughness).

1.3.1 Problem Statement

Plasma arc cutting can be characterized in terms of two distinct speeds. At cutting speeds above, the plasma jet does not cut through metal plate. At speeds below, the molten metal from the kerf sticks to the bottom of the plate, forming the so-called dross and how to properly select a plasma cutting system. Plasma can cut in a wide range of cutting parameters (currents, metal thicknesses and nozzle orifice diameters) for plasma arc cutting of stainless steel materials.

The plasma arc cutting process employs a plasma torch with a very narrow bore to produce a transferred arc to the work piece at an average current density of within the bore of the torch. The energy and momentum of the high-velocity plasma jet generated by the plasma torch melts, vaporizes and removes the metal from the region of impingement of the nozzle. Others problem is:

a. What type of metal is to cutting?
b. What is primary input power when cutting process?
c. How thick is the metal want to cut?
d. Traditional way of cutting takes a lot of time.
e. The effective way to conduct the cutting process for Stainless Steel.
f. The most important factors that influence the cutting process?
g. What are the best conditions to achieve optimum performances?

1.4 OBJECTIVES

This project was developed to study about the plasma arc cutting parameter in smooth cutting using straight polarity process. The main purposes of this project are listed below:

a) To study about the influence of Plasma Arc Cutting Parameters on Stainless Steel.

b) To design a series of experiment using the help of Design of Experiments (DOE) layout in order to study about Plasma Arc Cutting (PAC).

c) To study about the best combination of solution for maximizing the Material Removal Rate (MRR) and for minimizing the Surface Roughness (μm) with Taguchi Method .

1.5 SCOPE

Generally these projects will be developing within the scopes below:

1. This project focuses on the optimization of cutting parameters of Plasma Arc Cutting (PAC).

2. The material used to cut was Stainless Steel of specification ASTM A240 TP316 L.

3. Design of Experiments (DOE) layout will be used for testing and analyzing with Taguchi Method .

4. All of data was analyzed by using Minitab 15 Software to produce the best combination setting in plasma cutting for Stainless Steel.

5. The machine used will Silverin CNC Plasma Cutting Machine with Sharp line, Bombay make Burney 10 LCD to perform the machining operation.

1.6 INTRODUCTION TO PAC

Plasma arc cutting is not quite as involved as welding. The manner in cut the work piece will vary depending on the output of your plasma arc cutting machine and the thickness of material.

With engineering advances in PAC equipment, all metals that conduct electricity, whether they are common or exotic metals, can be cut economically with one process. Since the plasma arc cutting process is capable of hand-held or machine torch cutting metals ranging from thin gauge aluminium to 5-60 mm carbon or stainless steel. It can be used in many applications, including stack cutting, bevelling, shape cutting, gouging, and piercing in all positions. The PAC process is used in industries such as metal fabrication, construction, maintenance, metal salvage (scrap and recycling), automotive repair, metal art and sculpting.

When cutting metals at and below a machine's rated thickness, fix the gun at a 90-deg angle to the work piece. Make sure to take note of a machine's mm per minute capabilities on varying thicknesses, as that gives an idea of how fast to move across the cutting surface. When cutting materials at the rated size and above, it's recommended to slightly tilt torch into the work piece.

When needing to make multiple passes on a work piece to properly cut it and simply need a more powerful plasma cutting machine. Pay close attention to the machine's capabilities.

1.7 DESIGN OF EXPERIMENTS (DOE)

Design of Experiments (DOE) is a powerful statistical technique introduced by R.A. fisher in England in 1920s to study the effect of multiple variables simultaneously DOE can highly effective when:

a). Optimize product and process design , study the effect of multiple factor on process.

b). Study the influence of individual factors on the performance and determine which factor has more influence, and which one has less. It can also find which factor should have higher tolerance and which tolerance should be relaxed.

In industry, designed experiments can be used to systematically investigate the process or product variables that influence product quality. After you identify the process conditions and product components that influence product quality, you can direct improvement efforts to enhance a product's manufacturability, reliability, quality, and field performance.

Because resources are limited, it is very important to get the most information from each experiment you perform. Well designed experiments can produce significantly more information and often require fewer runs than haphazard or unplanned experiments. In addition, a well-designed experiment will ensure that you can evaluate the effects that you have identified as important [20].

.

Designed experiments are often carried out in four phases:

a) Planning,

b) Screening (also called process characterization),

c) Optimization, and

d) Verification.

Taguchi methods are most recent additions of tool kit design process for manufacturing engineers and quality assurance experts. In contrast to stastical process control which attempt to control the factors that adversely affect the quality of production. The significance of beginning quality assurance with an improved process or product design is not difficult to gauge. Taguchi method systematically reveals the complex cause and effect relationship between design parameter and performance.

These lead to building quality performance into process and product before actual production begins .Taguchi method have rapidly attained prominence because wherever they have been applied, they lead to the major reductions into process and products before actual production begins .The foundation of quality depend upon two premises :

1. Society incurs a loss any time the performance of product is not on target.

2. Product and process design require a systematic development, progressing stepwise through system design, parametric design and finally tolerance design.

The first point suggests that whenever the performance of a product deviates from its target performance, society suffer loss. Such a loss has two components: The manufacture incurs a loss when he repairs or rectified return or rejected product. The second point aims at quality engineering, a discipline that aims at engineering not only function but also quality performance into products and process .

The following seven points highlight the distinguish feature of Taguchi's approach which aimed at assuring quality:

1. Taguchi defined the term quality as the deviation from on target performance which
appears to be first paradox. According to him the quality of a manufactured product is the total loss generated by that product to the society from the time it is shipped.

2. In a competitive economy continuous improvement (CQI) and cost reduction are necessary.

3. A CQI programmed include continuous reduction in the variation of product performance characteristic in their target values.

4. Customer loss attribute to the product performance variation is often proportional to the square of the deviation performance characteristic from its target value.

5. The finally quality and cost of a product manufactured depends primarily on the engineering design of the product and its manufacturing process.

6. Variation in the product depends primarily on the engineering design of the product and its manufacturing process.

7. Statically planned experiments can efficiently and reliably identify the settings of the product and process parameters that reduce performance variations.

1.8 SIGNIFICANCE OF FINDINGS

From the thesis writing, it is important to get the best setting of Plasma Arc Cutting machine to maximize the Metal Removal Rate (MRR) and minimize the Surface Roughness (Ra) response during the advance material cutting process. From the result of the experiments using the Taguchi Method by Minitab 15 Software for Design of Experiments, the best combination of factors can be obtained, and the conclusions for the works that have been carried out can be determined.

1.9 SUMMARY

As a conclusion, the introduction to the problem has been specified. From the problem that arises, the solution has to be carried out. The objectives and the scopes have been determined in order to solve the problems

CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

Plasma cutting is a process that is used to cut steel and other metals (or sometimes other materials) using a plasma torch. In this process, an inert gas (Argon) is blown at high speed out of a nozzle and at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is sufficiently hot to melt the metal being cut and moves sufficiently fast to blow molten metal away from the cut. Plasma can also be used for plasma arc welding and other applications [24].

Plasma is typically an ionized gas. Plasma is considered to be a distinct state of matter, apart from gases, because of its unique properties. Ionized refers to presence of one or more free electrons, which are not bound to an atom or molecule. The free electric charges make the plasma electrically conductive so that it responds strongly to electromagnetic fields [27].

The Arc type uses a two cycle approach to producing plasma. First, a high-voltage, low current circuit is used to initialize a very small high intensity spark within the torch body, thereby generating a small pocket of plasma gas. This is referred to as the pilot arc. The pilot arc has a return electrical path built into the torch head. The pilot arc will maintain until it is brought into proximity of the work piece where it ignites the main plasma cutting arc. Plasma arcs are extremely hot and are in the range of 15,000 degrees Celsius.

Oxy fuel cuts by burning, or oxidizing, the metal it is severing. It is therefore limited to steel and other ferrous metals which support the oxidizing process.

Metals like aluminium and stainless steel form an oxide that inhibits further oxidization, making conventional oxyfuel cutting impossible. Plasma cutting, however, does not rely on oxidation to work, and thus it can cut aluminium, stainless and any other conductive material. While different gasses can be used for plasma cutting, most people today use compressed air for the plasma gas. In most shops, compressed air is readily available, and thus plasma does not require fuel gas and compressed oxygen for operation.

Plasma cutting is typically easier for the novice to master, and on thinner materials, plasma cutting is much faster than oxyfuel cutting. However, for heavy sections of steel (1inch and greater), oxyfuel is still preferred since oxyfuel is typically faster and, for heavier plate applications, very high capacity power supplies are required for plasma cutting applications [28] .

2.1 PRINCIPLE OF PLASMA ARC CUTTING

This process uses a concentrated electrical arc which melts the material through a high-temperature plasma beam. All conductive materials can be cut. Plasma cutting units with cutting currents from 20 to 1000 amperes to cut plates with inert gas, 5 to 160 mm thicknesses. Plasma gases are compressed air, nitrogen, oxygen or argon/ hydrogen to cut mild and high alloy steels, aluminium, copper and other metals and alloys [4].

The plasma arc process has always been seen as an alternative to the oxy-fuel process. In this part of the series the process fundamentals are described with emphasis being placed on the operating features and the advantages of the many process variants.

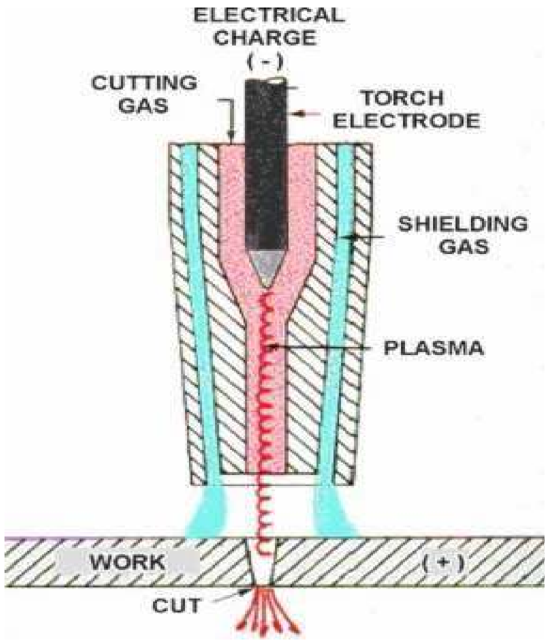


Fig 2.1 The principle of the plasma cutting

The plasma is additionally tied up by a water-cooled nozzle. With this energy densities up to 2x106 W/cm2 inside of the plasma beam can be achieved. Because of the high temperature the plasma expands and flows with supersonic velocity speed to the work piece (anode). Inside the plasma arc temperatures of 30 000oC can arise, that realize in connection with the high kinetic energy of the plasma beam and depending on the material thickness very high cutting speeds on all electrically conductive materials.

The term for advisable state of plasma arc is called stability of arc too. The stability of arc is keeping the plasma jet in desired form. It is possible to be provided by [4]:

a) Shape of Plasma Torch,

b) Streaming Jet,

c) Water.

We must monitor these parameters:

- Temperature and electrical conducting,
- Density of plasma jet,
- Diameter of plasma beam,
- Degree of the plasma beam focusing in output from nozzle.

For the cutting process first of all a pilot arc ignition by high voltage between nozzle and cathode takes place. This low- energy pilot arc prepares by ionization in parts the way between plasma torch and work piece. When the pilot arc touches the work piece (flying cutting, flying piercing), the main arc will start by an automatic increase in power

The basic principle is that the arc formed between the electrode and the work piece is constricted by a fine bore, copper nozzle. This increases the temperature and velocity of the plasma emanating from the nozzle. The temperature of the plasma is in excess of 20 000°C and the velocity can approach the speed of sound. When used for cutting, the plasma gas flow is increased so that the deeply penetrating plasma jet cuts through the material and molten material is removed in the efflux plasma.

The process differs from the oxy-fuel process in that the plasma process operates by using the arc to melt the metal whereas in the oxy-fuel process, the oxygen oxidizes the metal and the heat from the exothermic reaction melts the metal. Thus, unlike the oxy-fuel process, the plasma process can be applied to cutting metals which form refractory oxides such as stainless steel, aluminium, cast iron and non-ferrous alloys.

The power source required for the plasma arc process must have a drooping characteristic and a high voltage. Although the operating voltage to sustain the plasma is typically 100 to 160V, the open circuit voltage needed to initiate the arc can be up to 400V DC. On initiation, the pilot arc is formed within the body of the torch between the electrode and the nozzle. For cutting, the arc must be transferred to the work piece in the so-called 'transferred' arc mode. The electrode has a negative polarity and the work piece a positive polarity so that the majority of the arc energy (approximately two thirds) is used for cutting.

In the conventional system using a tungsten electrode, the plasma is inert, formed using either argon, argon-H2 or nitrogen. However, as described in Process variants, oxidizing gases, such as air or oxygen can be used but the electrode must be copper with hafnium. The plasma gas flow is critical and must be set according to the current level and the nozzle bore diameter. If the gas flow is too low for the current level, or the current level too high for the nozzle bore diameter, the arc will break down forming two arcs in series, electrode to nozzle and nozzle to work piece.

The effect of ‘double arcing’ is usually catastrophic with the nozzle melting. The quality of the plasma cut edge is similar to that achieved with the oxy fuel process. However, as the plasma process cuts by melting, a characteristic feature is the greater degree of melting towards the top of the metal resulting in top edge rounding, poor edge squareness or a bevel on the cut edge. As these limitations are associated with the degree of constriction of the arc, several torch designs are available to improve arc constriction to produce more uniform heating at the top and bottom of the cut.

The process variants have principally been designed to improve cut quality and arc stability, reduce the noise and fume or to increase cutting speed. The inert or uncreative plasma forming gas (argon or nitrogen) can be replaced with air but this requires a special electrode of hafnium or zirconium mounted in a copper holder, by shearing . The air can also replace water for cooling the torch. The advantage of an air plasma torch is that it uses air instead of expensive gases. It should be noted that although the electrode and nozzle are the only consumables, hafnium tipped electrodes can be expensive compared with tungsten electrodes.

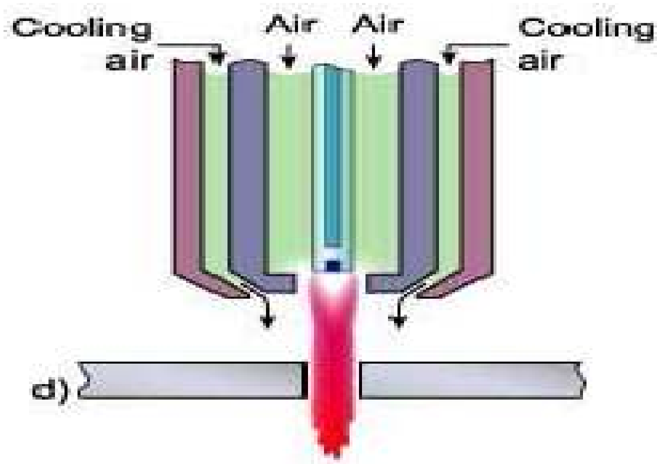


Figure 2.2: Air Plasma

This relatively new process differs from conventional, dry plasma cutting in that water is injected around the arc. The net result is greatly improved cut quality on virtually all metals, including mild steel. Today, because of advances in equipment design and improvement in cut quality, previously unheard of applications, such as multiple torches cutting of mild steel, are becoming common place [31].

2.1.1 Shielding and Cutting Gases for Plasma Cutting

Inert gases such as argon, helium, and nitrogen (except at elevated temperatures) are used with tungsten electrodes. Air may be used for the cutting gas when special electrodes made from water-cooled copper with inserts of metals such as hafnium are used. Recently, PAC units shielded by compressed air have been developed to cut thin-gauge materials.

Almost all plasma cutting of mild steel is done with one of three gas types:

1. Nitrogen with carbon dioxide shielding or water injection (mechanized)
2. Nitrogen-oxygen or air
3. Argon-hydrogen and nitrogen-hydrogen mixtures

The first two have become standard for high-speed mechanized applications. Argon-hydrogen and nitrogen-hydrogen (20 to 35 percent hydrogen) are occasionally used for manual cutting, but the formation of dross, a tenacious deposit of resolidified metal attached at the bottom of the cut, is a problem with the argon blend. A possible explanation for the heavier, more tenacious dross formed with argon is the greater surface tension of the molten metal. The surface tension of liquid steel is 30 percent higher in an argon atmosphere than in one of nitrogen.

Air cutting gives a dross similar to that formed in a nitrogen atmosphere. The plasma jet tends to remove more metal from the upper part of the work piece than from the lower part. This results in nonparallel cut surfaces that are generally wider at the top than at the bottom. The use of argon-hydrogen, because of its uniform heat pattern or the injection of water into the torch nozzle (mechanized only), can produce cuts that are square on one side and bevelled on the other side. For base metal over 3 inches thick, argon-hydrogen is frequently used without water injection [17].

2.1.2 Plasma Gas Selection

Air Plasma

1. Mostly used on ferrous or carbon based materials to obtain good quality a faster cutting speeds.
2. Only clan, dry air is recommended to use as plasma gas. Any oil or moisture in the air supply will substantially reduce torch parts life.
3. Air Plasma is normally used with air secondary.

Nitrogen Plasma

1. Can be used in place of air plasma with air secondary.
2. Provides much better parts life than air
3. Provides better cut quality on non-ferrous materials such as stainless steel and aluminium.
4. A good clean welding grade nitrogen should be used.

Argon/Hydrogen Plasma

1. A 65% argon/35% hydrogen mixture should be used.
2. Recommended use on 19mm and thicker stainless steel. Recommended for 12mm and thicker non-ferrous material. Ar/H_2 is not normally used for thinner non-ferrous material because less expensive gases can achieve similar cut quality.
3. Provides faster cutting speeds and high cut quality on thicker material to offset the higher cost of the gas.

4. Poor quality on ferrous materials.

Oxygen Plasma

1. Oxygen is recommended for cutting ferrous metals.
2. Provides faster cutting speeds.
3. Provides very smooth finishes and minimizes nitride build-up on cut surface (nitride build-up can cause difficulties in producing high quality welds if not removed).

2.1.3 Secondary Gas Selection for Plasma Cutting

Air Secondary

1. Air secondary is normally used when operating with air plasma and occasionally with nitrogen plasma.
2. Inexpensive - reduces operating costs
3. Improves cut quality on some ferrous materials

CO_2 Secondary

1. CO_2 secondary is used with nitrogen or Ar/H2 plasma.
2. Provides good cooling and maximizes torch parts life.
3. Usable on any ferrous or non-ferrous material
4. May reduce smoke when used with Ar/H_2 plasma.

Table 2.1 SUMMARY TABLE FOR GASE SELECTION

<table>
<tr><th rowspan="2">Gas</th><th rowspan="2">Material Thickness</th><th colspan="3">Material</th></tr>
<tr><th>Carbon Steel</th><th>Stainless Steel</th><th>Aluminium</th></tr>
<tr><td>Air Plasma
Air Secondary</td><td>Gage
Gage to 12mm
12mm and Up</td><td>Good / Excellent
Excellent
Excellent</td><td>Good / Excellent
Good
Fair</td><td>Good / Excellent
Good
Fair</td></tr>
<tr><td>Nitrogen Plasma
Air Secondary
Or CO_2 Secondary</td><td>Gage
Gage to 12mm
12mm and Up</td><td>Good / Excellent
Good / Excellent
Good / Excellent</td><td>Good / Excellent
Good / Excellent
Good / Excellent</td><td>Good / Excellent
Good / Excellent
Good / Excellent</td></tr>
<tr><td>Ar/H2 Plasma
N2 or CO2
Secondary</td><td>Gage to 6mm
6mm to 30mm
12mm and Up</td><td>NR
NR
NR</td><td>NR
Good
Good / Excellent</td><td>NR
Excellent
Excellent</td></tr>
</table>

2.2 PLASMA CUTTING CAPABILITY

Plasma is an effective means of cutting thin and thick materials alike. Hand held torches can usually cut up to 2 in (48 mm) thick steel plate, and stronger computer-controlled torches can pierce and cut steel up to 12 inches (300 mm) thick. Formerly, plasma cutters could only work on conductive materials, however new technologies allow the plasma ignition arc to be enclosed within the nozzle thus allowing the cutter to be used for non-conductive work pieces. Since plasma cutters produce a very hot and much localized cone to cut with they are extremely useful for cutting sheet metal in curved or angled shapes.

In this work, Plasma Arc Cutter was utilized to perform Stainless Steel (316 L) material cutting. The system and the process are the important elements when utilizing plasma arc cutting. It is important to know current plasma arc cutting research areas to plan the direction of this work so that this work would contribute information that will be useful in future.

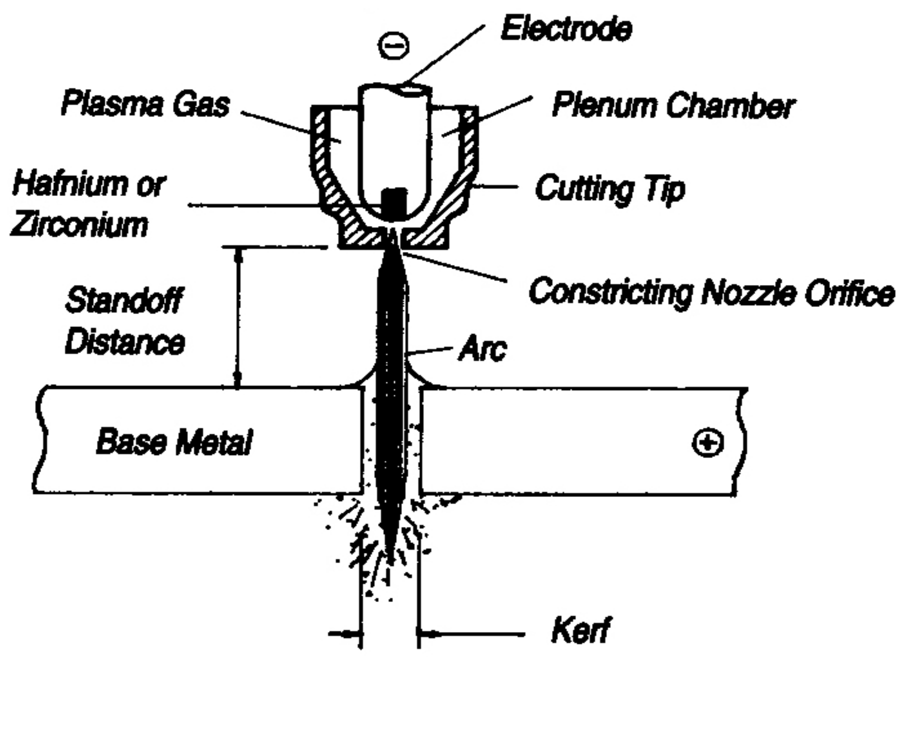


Fig 2.3Plasma Arc Setup

2.3 SYSTEM

Plasma arc cutting can increase the speed and efficiency of both sheet and plate metal cutting operations. Manufacturers of transportation and agricultural equipment, heavy machinery, aircraft components, air handling equipment, and many other products have discovered its benefits. Basically Plasma Arc Cutter comprises of 8 major parts such as air compressor, AC plug, power supply, plasma torch, ground clamp, electrode, nozzle and workpiece [17].

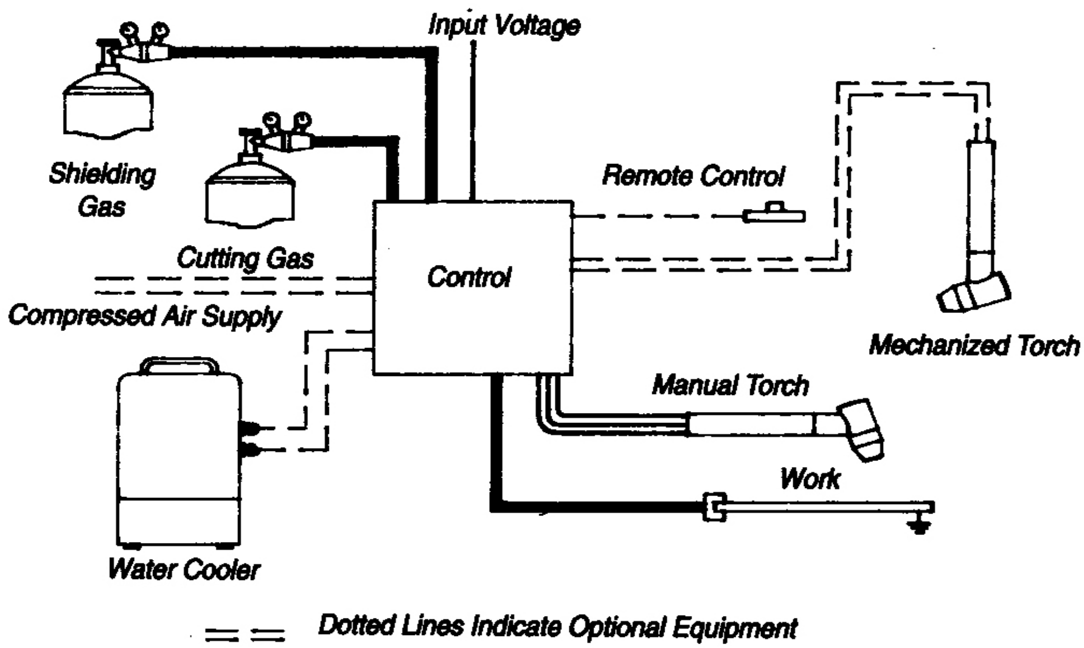


Figure 2.4 : Plasma Arc Cutter System

2.4 ARC STARTING CIRCUIT

The arc starting circuit is a high frequency generator circuit that produces an AC voltage of 5,000 to 10,000 volts at approximately 2 megahertz. This voltage is used to create a high intensity arc inside the torch to ionize the gas, thereby producing the plasma [35].

2.5 PROCESS

The basic plasma arc cutting system consists of a power supply, an arc starting circuit and a torch. These system components provide the electrical energy, ionization capability and process control that is necessary to produce high quality, highly productive cuts on a variety of different materials.

The power supply is a constant current DC power source. The open circuit voltage is typically in the range of 240 to 400 VDC. The output current (amperage) of the power supply determines the speed and cut thickness capability of the system. The main function of the power supply is to provide the correct energy to maintain the plasma arc after ionization.

The arc starting circuit is a high frequency generator circuit that produces an AC voltage of 5,000 to 10,000 volts at approximately 2 megahertz. This voltage is used to create a high intensity arc inside the torch to ionize the gas, thereby producing the plasma.

The Torch serves as the holder for the consumable nozzle and electrode, and provides cooling (either gas or water) to these parts. The nozzle and electrode constrict and maintain the plasma jet [35].

2.5 PLASMA TORCH

The Plasma cutting process is used with either a handheld torch or a mechanically mounted torch. There are several types and sizes of each, depending on the thickness of metal to be cut. Some torches can be dragged along in direct contact with the work piece, while others require that a standoff be maintained between the tip of the torch and work piece.

Mechanized torches can be mounted either on a tractor or a on a computer-controlled cutting machine or robot. Usually a standoff is maintained between the torch tip and work piece for best-cut quality. The standoff distance must be maintained with fairly close tolerances to achieve uniform results. Some mechanised torches are equipped with an automatic standoff controlling device to maintain a fixed distance between the torch and work piece. In other cases mechanical followers are used to accomplish this.

PAC torches operate at extremely high temperatures, and various parts of the torch must be considered to be consumable. The tip and electrode are the most vulnerable to wear during cutting, and cutting performance usually deteriorates as they wear. The timely replacement of consumable parts is required to achieve good quality cuts.

Modern plasma torches have self-aligning and self-adjusting consumable parts. As long as they are assembled in accordance with the manufacturer's instructions, the torch should require no further adjustment for proper operation [19].

Other torch parts such as shield cups, insulators, seals etc may also require periodic inspection and replacement if they are worn or damaged.

2.5.1 Torch Designs

The Single Flow Torch has only a flow of air for cutting. This is because its use is limited to lower amperage, thin gauge sheet metal cutting applications. It does not need a shielding gas flow to cool the torch because of the low amperage output required for cutting thin gauge sheet metal. The Dual Flow Torch has a flow of gas or air for the cutting plasma and shielding gas flow for the torch cooling. This is used for cutting thicker materials, which require higher amperages.

2.5.2 Torch Stand Off

"Torch stand-off" is the distance the outer face of the torch tip or constricting orifice nozzle is to the base metal surface. This standoff distance will be determined by the thickness of material being cut and the amperage required. Low heat build-up while cutting with less than 40 amperes may allow dragging the torch tip on the material. If a high build-up of heat is expected, a standoff distance of 1/16" to 1/8" will be required. This is easily accomplished with a Miller ICE torch with a "Drag Shield". The "Drag Shield" works with the flow dynamics of the torch to provide better cooling of the consumable parts for longer parts life. This permits the operator to drag the torch on the work piece while cutting at full output, which increases operator comfort and makes template cutting easier [19].

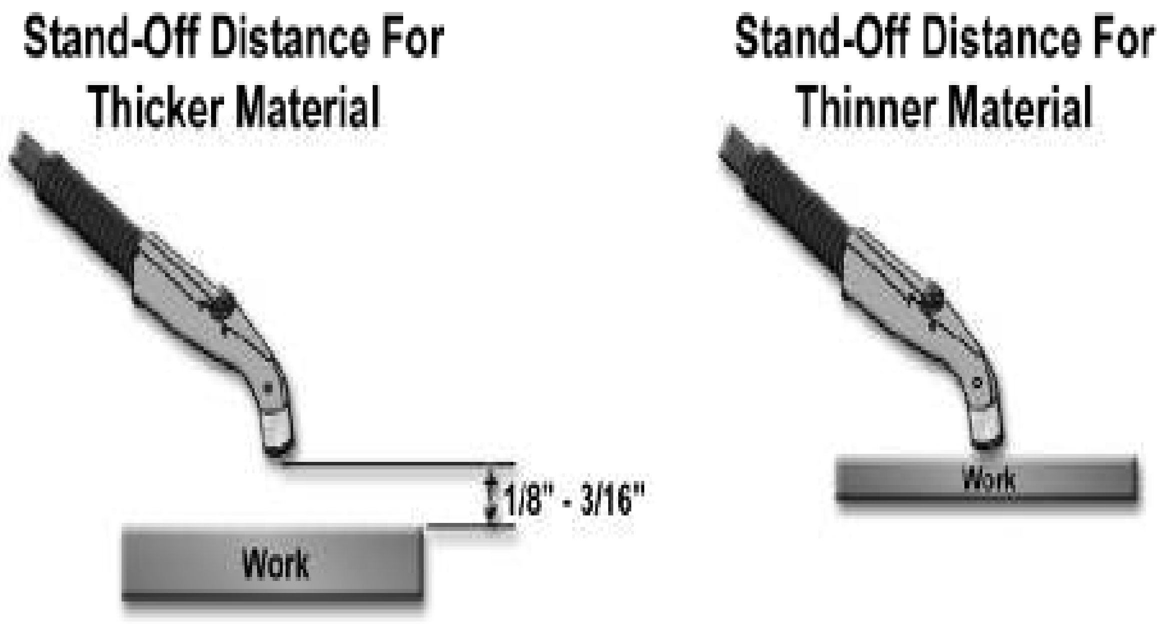


Fig 2.5 Torch Stand Off

2.5.3 Torch Consumables

The plasma torch is designed to generate and focus the plasma cutting arc. In either hand held or machine torches, the same parts are used: an electrode to carry the current form the power source, a swirl ring to spin the compressed air, a tip that constricts and focuses the cutting arc, and a shield and retaining ring to protect the torch.

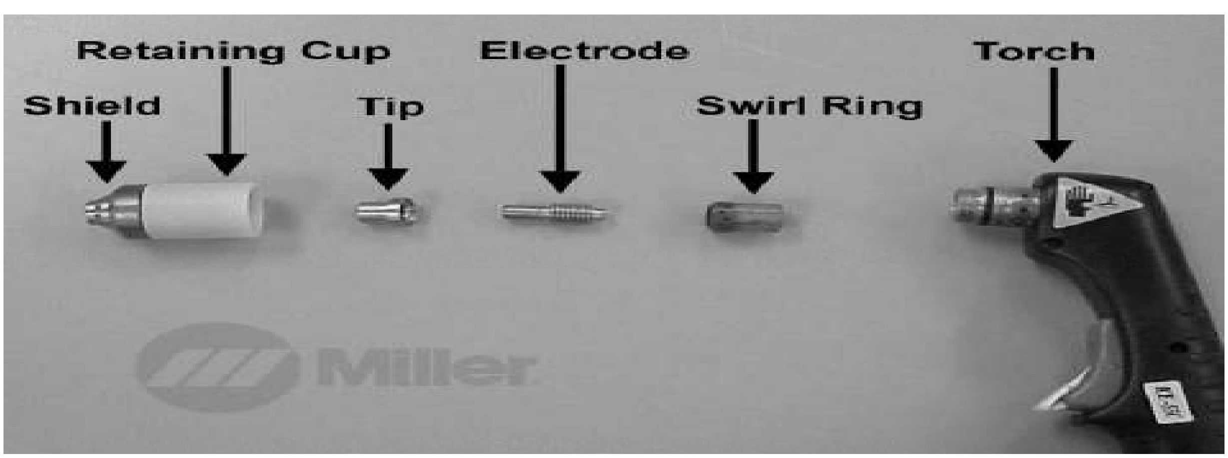


Fig. 2.6 Torch Breakdown

ELECTRODE. The purpose of the electrode is to provide a path for the electricity from the power source and generate the cutting arc. The electrode is typically made of copper with an insert made of hafnium. The Hafnium alloyed electrodes have good wear life when clean, dry compressed air or nitrogen is used (although, electrode consumption may be greater with air plasma than with nitrogen).

Fig 2.7 Electrode

SWIRL RING. The swirl ring is designed to spin the cutting gas in a vortex. The swirl ring is made of a high temperature plastic with angled holes that cause the gas to spin. Spinning the gas centres the arc on the electrode and helps to control and constrict the arc as it passes through the tip. The swirl ring on Miller plasma cutting equipment causes the gas to swirl in a clockwise direction.

Fig. 2.8 Swirl Ring

TIP. The purpose of the torch tip is to constrict and focus the plasma arc. Constricting the arc increases the energy density and velocity. The tips are made of copper, with a specifically sized hole or orifice in the centre of the tip. Tips are sized according to the amperage rating of the torch that they are to be used in [19].

Fig. 2.9 Tip

2.6 TAGUCHI DESIGN OVERVIEW

Dr. Genichi Taguchi is regarded as the foremost proponent of robust parameter design, which is an engineering method for product or process design that focuses on minimizing variation and/or sensitivity to noise. When used properly, Taguchi designs provide a powerful and efficient method for designing products that operate consistently and optimally over a variety of conditions.

In robust parameter design, the primary goal is to find factor settings that minimize response variation, while adjusting (or keeping) the process on target. After we determine which factors affect variation, we can try to find settings for controllable factors that will either reduce the variation, make the product insensitive to changes in uncontrollable (noise) factors, or both. A process designed with this goal will produce more consistent output. A product designed with this goal will deliver more consistent performance regardless of the environment in which it is used.

Engineering knowledge should guide the selection of factors and responses.

When interactions among control factors are likely or not well understood, we should choose a design that is capable of estimating those interactions. Minitab can help us to select a Taguchi design that does not confound interactions of interest with each other or with main effects.

Noise factors for the outer array should also be carefully selected and may require preliminary experimentation. The noise levels selected should reflect the range of conditions under which the response variable should remain robust. Robust parameter design uses Taguchi designs (orthogonal arrays), which allow us to analyze many factors with few runs. Taguchi designs are balanced, that is, no factor is weighted more or less in an experiment, thus allowing factors to be analyzed independently of each other [18].

Minitab provides both static and dynamic response experiments.

• In a static response experiment, the quality characteristic of interest has a fixed level.

• In a dynamic response experiment, the quality characteristic operates over a range of values and the goal is to improve the relationship between an input signal and an output response.

An example of a dynamic response experiment is an automotive acceleration experiment where the input signal is the amount of pressure on the gas pedal and the output response is vehicle speed. We can create a dynamic response experiment by adding a signal factor to a design − see Creating a dynamic response experiment. The goal of robust experimentation is to find an optimal combination of control factor settings that achieve robustness against (insensitivity to) noise factors. Minitab calculates response tables, linear model results, and generates main effects and interaction plots for:

• signal-to-noise ratios (S/N ratios, which provide a measure of robustness) vs. the control factors

• means (static design) or slopes (dynamic design) vs. the control factors

• standard deviations vs. the control factors

• natural log of the standard deviations vs. the control factors

Use the results and plots to determine what factors and interactions are important and evaluate how they affect responses. To get a complete understanding of factor effects it is advisable to evaluate S/N ratios, means (static design), slopes (dynamic design), and standard deviations [18].

2.7 WHAT IS TAGUCHI DESIGN?

A Taguchi design, or an orthogonal array, is a method of designing experiments that usually requires only a fraction of the full factorial combinations. An orthogonal array means the design is balanced so that factor levels are weighted equally. Because of this, each factor can be evaluated independently of all the other factors, so the effect of one factor does not influence the estimation of another factor.

In robust parameter design, we first choose control factors and their levels and choose an orthogonal array appropriate for these control factors. The control factors comprise the inner array. At the same time, we determine a set of noise factors, along with an experimental design for this set of factors. The noise factors comprise the outer array.

The experiment is carried out by running the complete set of noise factor settings at each combination of control factor settings (at each run). The response data from each run of the noise factors in the outer array are usually aligned in a row, next to the factors settings for that run of the control factors in the inner array

Each column in the orthogonal array represents a specific factor with two or more levels. Each row represents a run; the cell values indicate the factor settings for the run. By default, Minitab's orthogonal array designs use the integers 1, 2, 3... to represent factor levels. If we enter factor levels, the integers 1, 2, 3, ..., will be the coded levels for the design [18].

CHAPTER 3

PROJECT METHODOLOGY

3.1 SPECIMEN PREPARATION

16 test specimens having dimension 30mm x 30mm x 12 mm were prepared for the experimental work. The material for test specimen was Stainless Steel ASTM A 240 TP 316 L. Here L stands for Low Carbon Content.

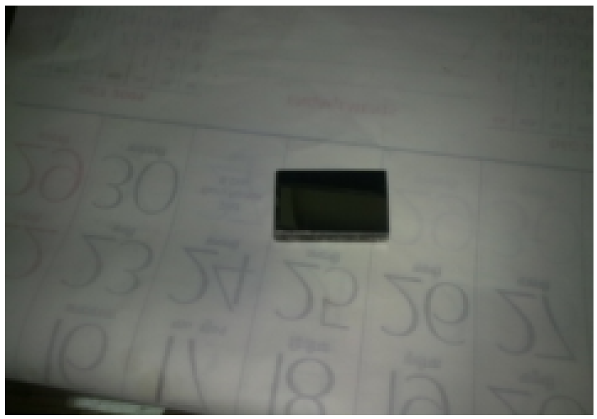


Fig. 3.1 Test Specimen

3.2 MATERIAL

Stainless Steel is essentially a low carbon steel which contains chromium at 10% or more by weight. It is this addition of chromium that gives steel its unique stainless, corrosion resisting properties. The chromium content allows the formation of a tough, adherent, invisible, corrosion resisting chromium oxide film on the steel surface.

Generally pipe flanges are manufactured from the Stainless Steel of grade 316 L. Here L stands for Low Carbon Content [37].

Table 3.1. Composition ranges for 316 grades of stainless steels.

Grade		C	Mn	Si	P	S	Cr	Mo	Ni	N
316	Min	-	-	-	0	-	16.0	2.00	10.0	-
	Max	0.08	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10
316L	Min	-	-	-	-	-	16.0	2.00	10.0	-
	Max	0.03	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10
316H	Min	0.04	0.04	0	-	-	16.0	2.00	10.0	-
	max	0.10	0.10	0.75	0.045	0.03	18.0	3.00	14.0	-

Table 3.2 Mechanical properties of 316 grade stainless steels

Grade	Tensile Strength (MPa)	Yield Str 0.2% Proof (MPa)	Elongation (% in 50mm)	Rockwell B (HR B) max	Brinell (HB) max
316	515	205	40	95	217
316L	485	170	40	95	217
316H	515	205	40	95	217

Good oxidation resistance in intermittent service to 870°C and in continuous service to 925°C. Continuous use of 316 in the 425-860°C range is not recommended if subsequent aqueous corrosion resistance is important. Grade 316L is more resistant to carbide precipitation and can be used in the above temperature range. Grade 316H has higher strength at elevated temperatures and is sometimes used for structural and pressure-containing applications at temperatures above about 500°C.

3.3EQUIPMENTS

Equipment for the experiment use is:

1. Plasma arc cutting system Silverin Make with Sharpline Bombay make Burny 10 LCD
2. Digital weight balancer equipment
3. The surface roughness tester (FORM TALY SURF) Taylor Hobson Make (U.K.)

3.3.1 Plasma Arc Cutting System

Plasma Arc Cutter used in this work is Silverin Make with Sharpline Bombay make Burny 10 LCD. Before cutting, worker always know plasma arc cuts all electrically conductive metals (Ox fuel is usually limited to steel), plasma arc cutting requires no preheating, turnaround time is fast, the process produces a small heat-affected zone.

Table 3.3 Technical Features

Technical Features	**Machine**
Supply voltage	3x400V - 50Hz
Rated power	30 kW
Operating pressure	5 bar
Primary fuse	16 A
Open circuit voltage	260 V
Pilot arc current	50 A

3.3.2 Digital Weight Balancer

The weight of the work pieces (specimens) before and after the cutting process need to be measuredin order to obtain the amount of Material Removal Rate (MRR).

3.3.3 Surface Roughness Tester

There are five steps to measure the surface roughness of specimens. Firstly, clamp the work piece of project use a clamping in the machine. And then, setting a prop of axis likes up and down, right or left direction. After finish setting, can start measured a work piece. Lastly, a data value for roughness can print out after finish measured. The surface roughness tester (FORM TALY SURF) used in this work, with the following specifications:

Manufacturer: Taylor Hobson, U.K,

Travelling length: 01mm-50mm,

Force: 4mN,

Stylus: Diamond 2µm tip radius,

Resolution: 16nm/1.0mm,

Software: Form ultra software

3.3.4 Power Supply

The power supply required depends on the material thickness and cutting speeds desired. Increasing the power increases the cutting speed or enables thicker metals to be cut without slow down. Power ratings are commonly between 20 and 200 kW.

Fig3.2 DC Power Supply Source

3.4 DESIGN FACTORS

Design of Experiments technique has been utilized to obtain the best combination of design factors to achieve optimum performance measures. Plasma Arc Cutting involves several input parameters to be considered during machining process. In this thesis, the combination factors such as Gas Pressure [bar], Current Flow Rate [A], Cutting Speed [mm/min] and Arc Gap [mm] are considered. These factors are the most important to have the best value for Material Removal Rate (MRR) and Surface Roughness (Ra) when cutting material like Stainless Steel or Nickel Base Alloy etc.

Gas Pressure

According to Larry Jeffus, *"Principle and Application of Welding"* Sixth Addition, almost any gas or gas mixture can be used today for the PAC process. Normally Nitrogen or Argon with 0-35% Hydrogen is used for cutting Stainless Steel material. We used Argon with 0-35% Hydrogen for our experiment purpose. It is important to have the correct gas flow rate for the size tip, metal type and thickness. Too low a gas flow will result in a cut having excessive dross and sharply bevelled sides. Too high a gas flow will produce a poor cut because of turbulence in the plasma stream and waste gas. Controlling the pressure is one way of controlling gas flow [23].

Current Flow Rate

Current flow rate is the value of current given during cutting process. The cause of the burn-through was the increase in the cutting current or the decrease in the cutting speed. When the cutting current increases or the cutting speed decreases, the stable state of the keyhole changes accordingly. If the cutting current and the flow rate of the plasma gas are increased and/or the cutting speed is decreased, the process will withstand larger variations in the cutting parameters .

Cutting Speed

The best way to judge cutting speed is to look at the arc as it exits the bottom of the work piece. Observe the angle of the cutting arc through the proper welding lens. If cutting with air, the arc should be vertical straight down, or zero degrees as it exits the bottom side of the cut. If cutting with nitrogen or argon/hydrogen, then the correct cutting speed will produce a trailing arc (that is, an exit arc that is opposite to the direction of torch travel).

The torch speed needs to be adjusted to get a good-quality cut. A cutting speed that is too slow or too fast will cause cut quality problems. In most metals there is a window between these two extremes that will give straight, clean, dross free cuts.

Arc Gap

Arc gap is the gap between the plasma arc cutter torch and welding electrodes with the work piece [23] .

3.5 PLASMA ARC CUTTING RESPONSE

There are two Plasma Arc Cutting responses measured in this study, known as:

i. Material Removal Rate (MRR)

ii. Surface Roughness (Ra)

3.5.1 MATERIAL REMOVAL RATE

The material removal rate, MRR, can be defined as the volume of material removed divided by the machining time. Material Removal Rate (MRR) is defined by:

MRR = WRW/T [g/min]

Where,

WRW: workpiece removal weight (g)

T: cutting time(s)

WRW is the weight different between before and after work piece cutting. The volume different can be calculated when information regarding material density available. The relation between WRW and WRV is given as follow:

WRV = WRW/ρ

Where,

ρ : Work piece density (g/ mm3)

The density of the Nickel-Base Alloys is 8 g/cm3 or 0.008g/mm3.

3.5.2 SURFACE ROUGHNESS

Roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough, if they are small the surface is smooth. Roughness is typically considered to be the high frequency, short wavelength component of a measured surface. Surface roughness normally measured.

Roughness plays an important role in determining how a real object will interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces (see tribology). Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion.

In this thesis, the average surface roughness is measured and calculated. The average surface roughness is the integral of the absolute value of the roughness profile height over the evaluation length and is denoted by the following equation.

$$R_a = \frac{1}{L}\int_0^L |Y(x)|dx$$

Where L is the length taken for observation, and Y is the ordinate of the profile curve [9].

CHAPTER 4

DESIGN OF STUDY

4.1 OUTLINE OF THESIS WORK

It is found already many work has been done in MRR and Surface finish but very little work has been done on optimization of Plasma Arc Cutting. Here in my thesis work I will try to find out optimal value of MRR and SURFACE ROUGHNESS (Ra).

For this I consult to Fabrication Division of BHEL, Bhopal, they suggested that Stainless Steel (316L) materials are cheaply available and widely used in Plasma Cutting Machine .Taguchi method using design of experiments approach can be used to optimize a process Here we will to apply D.O.E approach for modelling of MRR in PAC process and the various input parameters will be taken under experimental investigation and then model will be prepared then again experimentation work will be performed. The results obtain will be analyzed and the models will be produced by using MINITAB software. This will help in improving the effective and efficient working of the PAC process.

Various Input parameters

- Voltage
- Current Flow Rate
- Arc Gap
- Kerf (width of cut)
- Cutting Speed
- Material Type and Thickness
- Cutting gas Pressure

After extensive brain storming with the experts of Fabrication Division of BHEL Bhopal, it has been found that above are important input parameters for studying material remove rate. As I am going to perform my work on Silverin make Plasma

Arc Cutting Machine No. B/0/2163 and after literature review four main input parameters selected are **Gas Pressure,** C**urrent, Cutting Speed, and Arc Gap.**

The other two parameters **kerf (5mm) and Material Thickness (12mm)** is kept fixed for the whole experiment. The material used is **Stainless Steel ASTM A240TP316L** in the overall experiment.

4.2 DESIGN OF EXPERIMENT

The objective of this research work is to study MRR and Surface roughness, the design variables can be summarized as follows:

a) Two levels of the Gas Pressure (6Bar and 7Bar).

b) Two levels of Current Flow Rate (150A and 200A).

c) Two levels of Cutting Speed (400mm/min and 600mm/min).

d) Two levels of Arc Gap (2mm and 4mm)

For conducting the experiments, it has been decided to follow the Taguchi method of experimental design and an appropriate orthogonal array is to be selected after taking into consideration the above design variables. Out of the above listed design variables, the orthogonal array was to be selected for four design variables (namely Gas Pressure, Current, Cutting Speed and Arc gap) which would constitute the L16 orthogonal array.

The two most important outputs are Material Removal Rate and Surface Roughness the same have been selected as response parameters for this research work also. The effect of the variation in input process parameter will be studied on these two response parameters and the experimental data will be analyzed as per Taguchi method to find out the optimum machining condition and percentage contribution of each factor. The following machining parameters were kept fixed.

Table 4.1 Fixed Machining Parameters

S. No.	Machining Parameters	Fixed Value
1	**Material Type**	**Stainless Steel (316 L)**
2	**Material Thickness**	**12 mm**
3	**Kerf**	**5mm**
4	**Operating Voltage**	**200 V**

4.3 SELECTION OF ORTHOGONAL ARRAY AND PARAMETER ASSIGNMENT

In this experiment, there are four parameters at two levels each. The degree of freedom (DOF) of a two level parameter is 2 (Number of Levels minus 1), hence total DOF for the experiment is 4. The DOF of the orthogonal array selected should have higher than that of total DOF of the experiment.

Table 4.2 Parametric Level Assignment

Parameter	Unit	Level 1	Level 2	DOF
Gas Pressure	bar	5	6	1
Current Flow Rate	ampere	150	200	1
Cutting Speed	mm/min	400	600	1
Arc Gap	mm	2	4	1

4.3.1 Standard L16 Array with (2*4) :- Column number 1 2 4 and 8 of L16(2**15) Array is used for this experiment:-

Table 4.3 Experimental Layout in Coded Factor Levels

Runs	Gas Pressure	Current	Cutting Speed	Arc Gap
1	1	1	1	1
2	1	1	1	2
3	1	1	2	1
4	1	1	2	2
5	1	2	1	1
6	1	2	1	2
7	1	2	2	1
8	1	2	2	2
9	2	1	1	1
10	2	1	1	2
11	2	1	2	1
12	2	1	2	2
13	2	2	1	1
14	2	2	1	2
15	2	2	2	1
16	2	2	2	2

The above table displays the L16 (2*4) Taguchi design (orthogonal array). L16 means 16 runs. 2*4 means 4 factors with 2 levels each. This array is orthogonal; factor levels are weighted equally across the entire design. The table columns represent the control factors, the table rows represent the runs (combination of factor levels), and each table cell represents the factor level for that run.

4.4 SIGNAL TO NOISE (S/N) RATIO

Noise factors are those that are either too hard or uneconomical to control even though they may cause unwanted variation in performance. It is observed that on target performance usually satisfies the user best, and the target lies under acceptable range of product quality are often inadequate. If Y is the performance characteristic measured on a continuous scale when ideal or target performance is T then according to Taguchi the loss caused L(Y) can be modeled by a quadratic function as shown in equation (1)

$L(Y) = K\ (Y\text{-}T^2)$........................ (1)

The objective of robust design is specific; robust design seeks optimum settings of parameters to achieve a particular target performance value under the most noise condition. Suppose that in a set of statistical experiment one finds a average quality characteristic to be μ and standard deviation to be σ. Let desired performance be $\mu1$ .Then one make adjustment in design to get performance on target by adjusting value of control factor by multiplying it by the factor (μ_0/μ) . Since on target is goal the loss after adjustment is due to variability remaining from the new standard deviation. Loss after adjustment shown in equation (2):

$$\mathbf{k}(\mu_0|\mu)^2\ \sigma^2 \ldots\ldots\ldots (2)$$

The factor $\frac{\mu^2}{\sigma^2}$ reflects the *ratio of average performance* μ^2(which is the signal) and σ^2(*the variance* of performance) the noise. Maximizing $\frac{\mu^2}{\sigma^2}$ or S/N ratio therefore become equivalent to minimizing the loss after adjustment. Finding a correct objective function to maximize in an engineering design problem is very important.

Depending upon the type of response, the following three types of S/N ratios are employed in practice:

Larger is Better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the larger-is-better S/N ratio using base 10 log is:

$S/N = -10*\log(\text{Sum of } (1/Y^2)/n)$

Where

Y = responses for the given factor level combination and,

n = number of responses in the factor level combination.

Smaller is Better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the smaller-is-better S/N ratio using base 10 log is:

$S/N = -10*\log(\text{Sum of}(Y^2)/n)$

Where Y = responses for the given factor level combination and

n = number of responses in the factor level combination.

- In my thesis work MRR is considered *larger is better.* Value of MRR is measured by difference between initial and final weight after machining
- Surface roughness of specimen is considered as *smaller is better.* Surface roughness is measured by Taylor Hobson Make Talysurf Instrument.

4.5 ANOVA (Analysis of Variance)

The purpose of the statistical analysis of variance (ANOVA) is to investigate which design parameter significantly affects the material removal rate and surface roughness. Based on the ANOVA, the relative importance of the machining parameters with respect to material removal rate and surface roughness is investigated to determine more accurately the optimum combination of the machining parameters.

Two types of variations are present in experimental data:

1. Within treatment variability
2. Observation to observation variability

So ANOVA helps us to compare variabilities within experimental data. In my thesis ANOVA table is made with help of **MINITAB 15** software. When performance varies one determines theaverage loss by statistically averaging the quadratic loss. The average loss is proportional to the *mean squared error* of Y about its target T. The initial techniques of the analysis of variance were developed by the statistician and geneticist R. A. Fisher in the 1920s and 1930s, and are sometimes known as Fisher's ANOVA or Fisher's analysis of variance, due to the use of Fisher's *F-distribution* as part of the test of statistical significance.

4.5.1 Various formulas for ANOVA:

Degrees of freedom (DF)

Indicates the number of independent elements in the sum of squares. The degrees of freedom for each component of the model are:

DF (Factor) = r-1

DF (Error) = $n_t - r$

Total = $n_t - 1$

Where n_T = the total number of observations and r = the number of factor levels.

Sum of squares (SS)

The sum of squared distances. SS Total is the total variation in the data. SS (Factor) is the deviation of the estimated factor level mean around the overall mean. It is also known as the sum of squares between treatments. SS Error is the deviation of an observation from its corresponding factor level mean. It is also known as error within treatments. The calculations are:

SS (Factor) = $S\ n_i\ (y_{i.} - y_{..})^2$

SS Error = $S_i\ S_j\ (y_{ij} - y_{i.})^2$

SS Total = $S_i\ S_j\ (y_{ij} - y_{..})^2$

Where $y_{i.}$ = mean of the observations at the i^{th} factor level,

$y_{..}$ = mean of all observations and

y_{ij} = value of the j^{th} observation at the i^{th} factor level.

Pure sum of square

SS' (Factor) = SS (Factor) – DF (Factor) * MS (Error)

Mean square (MS)

The calculations for the mean square for the factor and error are:

MS (Factor) = SS (Factor)/ DF (Factor)

MS (Error) = SS (Error)/ DF (Error)

F Value

A test to determine whether the factor means are equal or not. The formula is:

F = MS (Factor)/ MS (Error)

The degrees of freedom for the numerator are r - 1 and for the denominator are n_T - r. Larger values of F support rejecting the null hypothesis that the means are equal.

CHAPTER-5

EXPERIMENTAL ANALYSIS

5.1 EXPERIMENTAL LAYOUT

Since in my thesis work there are four factors and two levels for each which are shown below:

Table 5.1 Values of variables at different level

Control Factors	**Unit**	**Level 1**	**Level 2**	**DOF**
Gas Pressure	bar	5	6	1
Current Flow Rate	ampere	150	200	1
Cutting Speed	mm/min	400	600	1
Arc Gap	mm	2	4	1

After deciding parameters and levels as shown above orthogonal array L16 decided as per degree of freedom of each factor and dof of interaction among the parameters. Data of parameter was collected in such a way that it shouldn't damage or cause any accident to operator and as per literature review. Now perform experiment as per orthogonal array (L16) on **Plasma Arc Cutting Machine Number B/0/2163**, output like MRR and surface roughness is being given in tabulated form. After the experimental results have been obtained, analysis of the results was carried out analytically as well as graphically. Graphical analysis is done by MINITAB, shows interactions of all parameters. Then ANOVA of the experimental data has been done to calculate the contribution of each factor in each response. Then we calculated S/N ratio for MRR and surface roughness of specimens.

Then we obtain optimal conditions has been calculated for MRR and surface roughness of specimen. The following table shows readings of MRR and surface roughness at each experiment, it also shows S/N ratio for MRR and surface roughness at each experiments.

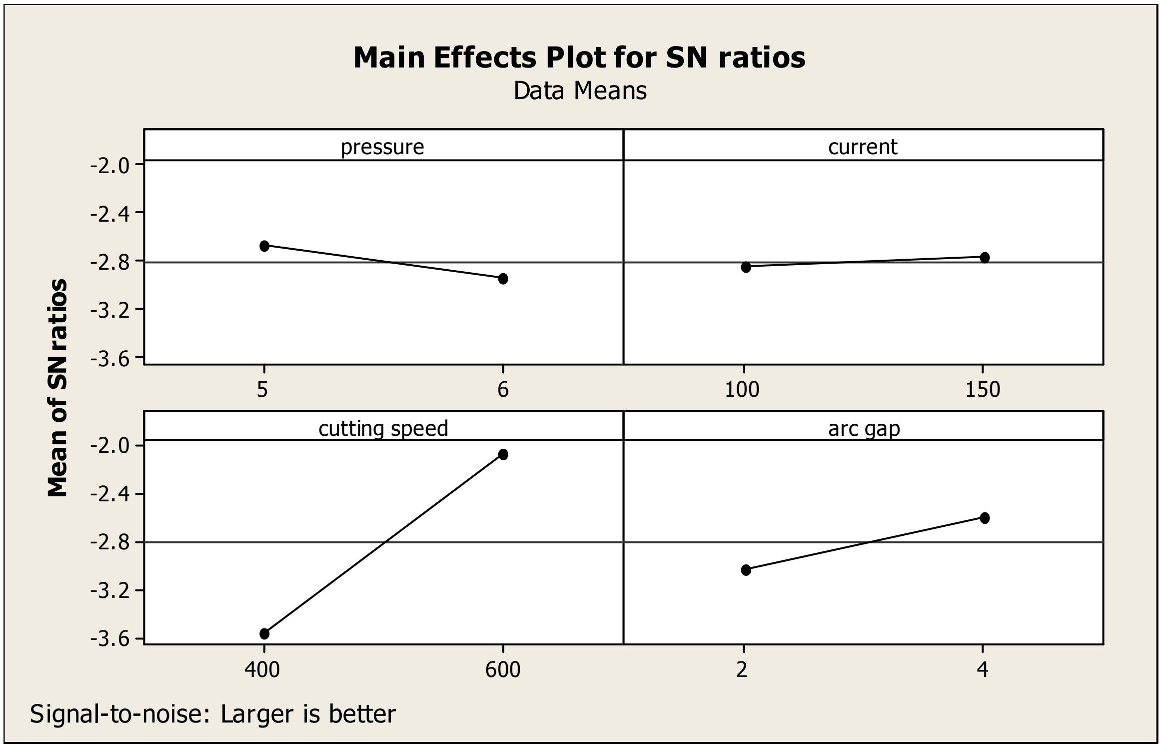
Table 5.2 Calculation Sheet for MRR and Surface Roughness

Exp No.	**Mass 1 (Before Cutting)**	**Mass 2 (After Cutting)**	**Mass Loss (g)**	**Time Taken (Sec)**	**MRR (g/Sec)**	**Surface roughness (μm)**
1	90	61.2	28.8	45	0.640000	3.834
2	87	58.6	28.4	45	0.631111	3.688
3	85.4	56.4	29	40	0.725000	4.393
4	79.05	49.65	29.4	36	0.816667	4.679
5	98.54	69.74	28.8	40	0.720000	3.180
6	79.69	52.69	27	36	0.750000	3.458
7	102.77	73.87	28.9	36	0.802778	4.571
8	99.48	70.68	28.8	35	0.822857	3.568
9	82.63	56.23	26.4	40	0.660000	3.255
10	82.67	53.77	28.9	39	0.741026	3.688
11	72.4	43	29.4	38	0.773684	3.951
12	73	43.2	29.8	37	0.805405	3.958
13	93.45	64.65	28.8	49	0.587755	2.352
14	89.1	60.9	28.2	47	0.60000	2.636
15	86.75	58.55	28.2	37	0.762162	3.969
16	93.27	64.77	28.5	35	0.814286	4.123

Table 5.3 Experimental Layout and S/N ratios for MRR and Surface Roughness (Actual Factor Levels)

Exp No.	Pressure (Bar)	Current (A)	Speed (mm/min)	Arc Gap (mm)	MRR (g/Sec)	S/N ratio for MRR	SR Ra (μm)	S/N ratio for SR
1	5	150	400	2	0.640000	-3.87640	3.834	11.6730
2	5	150	400	4	0.631111	-3.99788	3.688	11.3358
3	5	150	600	2	0.725000	-2.79324	4.393	12.8552
4	5	150	600	4	0.816667	-1.75910	4.679	13.4031
5	5	200	400	2	0.720000	-2.85335	3.180	10.0485
6	5	200	400	4	0.750000	-2.49877	3.458	10.7765
7	5	200	600	2	0.802778	-1.90809	4.571	13.2002
8	5	200	600	4	0.822857	-1.69351	3.568	11.0485
9	6	150	400	2	0.660000	-3.60912	3.255	10.2510
10	6	150	400	4	0.741026	-2.60334	3.688	11.3358
11	6	150	600	2	0.773684	-2.22873	3.951	11.9341
12	6	150	600	4	0.805405	-1.87971	3.958	11.9495
13	6	200	400	2	0.587755	-4.61607	2.352	7.4287
14	6	200	400	4	0.60000	-4.43697	2.636	8.4189
15	6	200	600	2	0.762162	-2.35905	3.969	11.9736
16	6	200	600	4	0.814286	-1.78446	4.123	12.3043

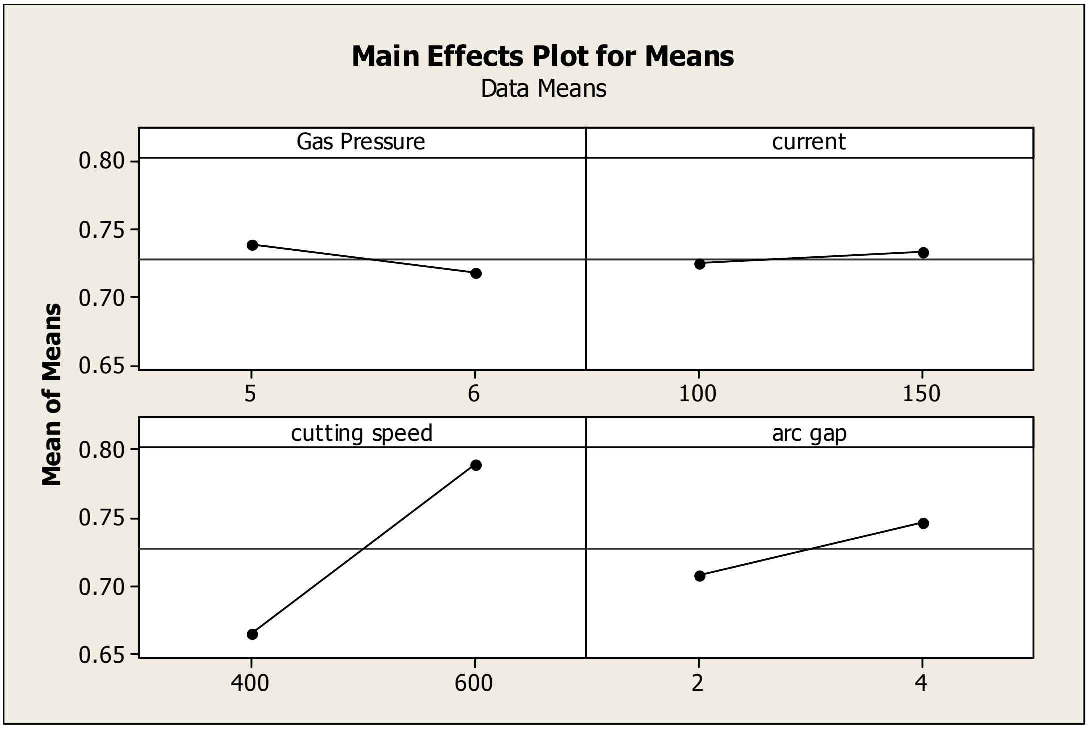
5.2 EXPERIMENTAL RESULTS FOR MRR



Graph 5.1 Effects of various factors on S/N Ratio of MRR

By using MINITAB software we obtain some interactions if we look at the graph we will observe that with increase in Gas Pressure MRR S/N ratio is decreasing. Material removal rate increases with increase in Current, Cutting Speed and Arc gap.

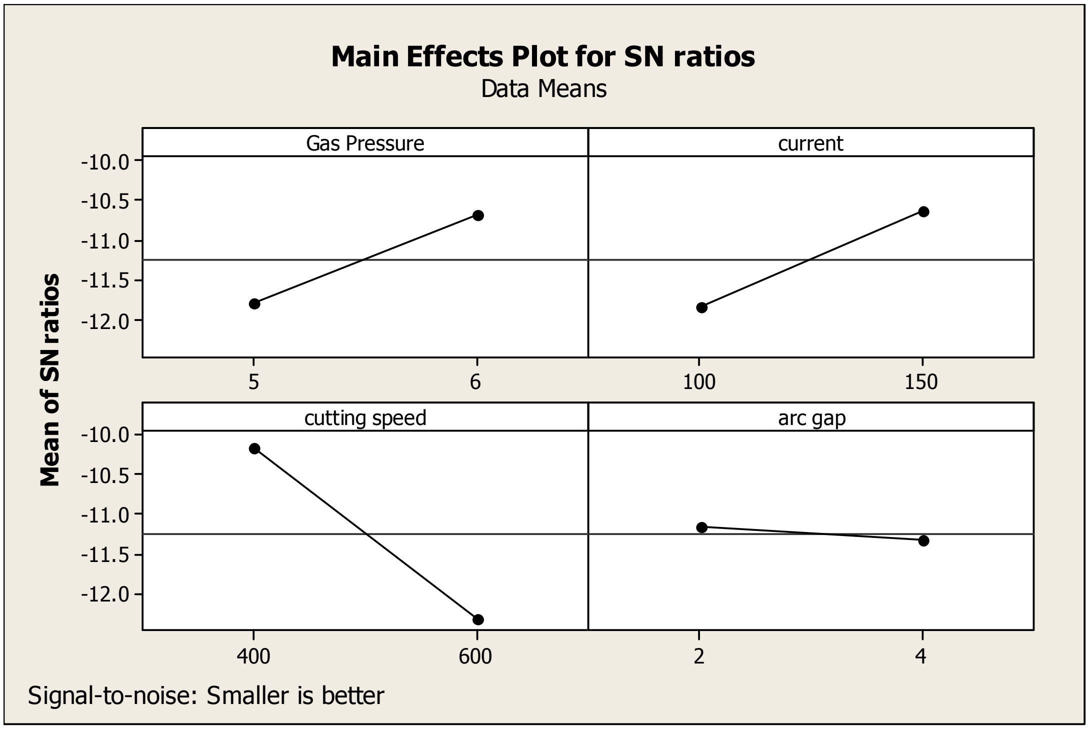
Main Effect Plot for Mean of MRR



Graph 5.2 Effects of various factors on Mean of MRR

With the above graph of mean of MRR and various factors, we can observe that MRR is decreasing with increase in Gas Pressure and MRR is increasing with increase in Current, Cutting Speed and Arc Gap.

5.3 EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS



Graph 5.3 Effects of various factors on S/N Ratio of SR

Above graph represent the effect of parameters on Surface Roughness. It can be seen that as value of Gas Pressure and Current increases, S/N ratio of Surface roughness also increases. However S/N ratio of Surface roughness decreases with increase in the Cutting Speed and Arc Gap.

5.4 ANALYSIS OF VARIANCE (ANOVA)

Since as already stated ANOVA help us to identify which parameter is important for us after literature review following ANOVA table is obtained for MRR and Surface roughness .Minitab 15 software is used for statistical calculation purpose.

Table 5.4 ANOVA Table for MRR

Parameters	DOF	SS	MS	F	P	Contribution (%)
Gas Pressure	1	0.2854	0.2854	0.68	0.427	1.92
Current	1	0.0223	0.0223	0.05	0.822	1.5
Cutting Speed	1	9.1295	9.1295	21.75	0.001	61.44
Arc Gap	1	0.8056	0.8056	1.92	0.193	5.42
Residual Error	11	4.6172	0.41975			31.07
Total	15	14.8601				100

TablE 5.4. shows the Analysis of Variance (ANOVA) for MRR response. The important information can be obtained here is the percentage influence of all factors over responses. P value less than 0.0500 indicate model terms are significant.

In this case Cutting Speed is significant model term. Values greater than 0.1000 indicate the model terms are not significant. The percentage contribution by each of the process parameter in the total sum of squared deviation SS_t can be used to evaluate the importance of the process parameter change on the quality characteristic.

Table 5.5 ANOVA Table for Surface Roughness (Ra)

Parameters	DOF	SS	MS	F	P	Contribution (%)
Gas Pressure	1	4.7795	4.7795	5.45	0.040	12.22
Current	1	5.6862	5.6862	6.48	0.027	14.53
Cutting Speed	1	18.9228	18.9228	21.58	0.001	48.36
Arc Gap	1	0.0912	0.0912	0.10	0.753	0.23
Residual Error	11	9.6452	0.8768			24.65
Total	15	39.1250				100

From table 5.5 we can conclude that Gas Pressure, Current and Cutting Speed are significant terms because their P values are less than 0.05. P values greater than 0.01 indicates that model terms are not significant. The P value for the factor Arc Gap is 0.753 which is not significant. There is 75.3% chance that a this large could occur due to noise. The percentage contribution by each of the process parameter in the total sum of squared deviation SS_t can be used to evaluate the importance of the process parameter change on the quality characteristic.

5.5 CONFIRMATION TEST

From S/N ratio and mean of each level of every factor we will construct response table for MRR and Surface Roughness which are given below:

Table 5.6 Response table for S/N ratio of MRR

Level	Gas Pressure	Current	Cutting Speed	Arc Gap
1	-2.673	-2.843	-3.561	-3.031
2	-2.940	-2.769	-2.051	-2.582
Effect (Δ)	0.267	0.075	1.511	0.449
Rank	3	4	1	2

From above response table and main effect plot of MRR we can conclude that the optimum condition for MRR is, A1B2 C2 D2 i. e.

Gas Pressure: 5 Bar

Current: 150 A

Cutting Speed: 600 mm/min

Arc Gap: 4mm

Similarly we can create the response table for S/N ratio of Surface Roughness.

Table 5.7 Response table for S/N ratio of Surface Roughness

Level	Gas Pressure	Current	Cutting Speed	Arc Gap
1	-11.79	-11.84	-10.16	-11.17
2	-10.70	-10.65	-12.33	-11.32
Effect (Δ)	01.09	1.19	2.18	0.15
Rank	3	2	1	4

From the above table and main effect graph of Surface Roughness we can say that optimal levels of parameters for SR are A2B2C1D1 i. e.

Gas Pressure: 6 Bar

Current: 150 A

Cutting Speed: 400 mm/min

Arc Gap: 2 mm

After evaluating the optimal parameter settings, the next step of the Taguchi approach is to predict and verify the enhancement of quality characteristics using the optimal parametric combination. The estimated Optimum S/N ratio using the optimal level of the design parameters can be calculated:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} (\overline{\eta}_i - \eta_m)$$

where ,

η_m is the total mean of the multi response signal-to-noise ratio,

$\overline{\eta}_i$ is the mean of the multi-response signal-to noise ratio at the optimal level, and q is the number of the process parameters that significantly affect the multiple quality characteristics.

Based on the above equation the estimated multi response signal to noise ratio can be obtained.

5.5.1Prediction of Optimum Value of MRR:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} (\bar{\eta}_i - \eta_m)$$

Here η_m = **-2.80625**

Optimum S/N Ratio for MRR = -2.80625 + (-2.673 + 2.80625) + (-2.769 + 2.80625) +

(- 2.051 + 2.80625) + (-2.582 + 2.80625)

$\hat{\eta}$ **= - 1.6525**

And the corresponding value of MRR = $Y_{opt}^2 = \frac{1}{10^{\frac{-\eta_{opt}}{10}}}$ = 0.6829202

Predicted Optimum Value of MRR,	**Y_{opt} = 0.8264 g/sec**

5.5.2Prediction of Optimum Value of SR :

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} (\overline{\eta}_i - \eta_m)$$

Here η_m **= - 11.245**

Optimum S/N Ratio for SR = -11.245 + (-10.70 + 11.245) + (-10.65 + 11.245) + (- 10.16 + 11.245) + (-11.17 + 11.245)

$$\hat{\eta} = \mathbf{-\ 8.945}$$

And the corresponding value of SR = $Y_{opt}^{2} = 10^{\frac{-\eta_{opt}}{10}}$ = 7.8433

Predicted Optimum Value of SR	$\mathbf{Y_{opt} = 2.8006\ \mu m}$

Once the optimal value of MRR and SR is predicted, the final step is to verify the improvement of the quality characteristic using the optimal level of the process parameters.

Table 5.8 Confirmation Test Result for MRR

Number	**Pressure (Bar)**	**Current (A)**	**Cutting Speed (mm/min)**	**Gap (mm)**	**MRR (g/sec)**
1	**5**	**150**	**600**	**4**	**0.8345**
2	**5**	**150**	**600**	**4**	**0.8393**
3	**5**	**150**	**600**	**4**	**0.8254**
				Average	**0.8331**

Table 5.9 Confirmation Test Result for SR (Ra)

Number	**Pressure (Bar)**	**Current (A)**	**Cutting Speed (mm/min)**	**Gap (mm)**	**SR (μm)**
1	**6**	**150**	**400**	**2**	**2.672**
2	**6**	**150**	**400**	**2**	**2.452**
3	**6**	**150**	**400**	**2**	**2.780**
				Average	**2.635**

After performing experiment as per given optimum levels for MRR and SR following results obtained:

Table 5.10 Summary Table for Results

MRR (g/sec)	Optimum value of A1B2C2D2 = 0.8264	Experimental result of A1B2C2D2= 0.8331	Percentage = 0.81%
Surface Roughness (μm)	Optimum value of A2B2C1D1 = 2.8006	Experimental result of A2B2C1D1= 2.635	Percentage = 5.91%

So we can say that there is 0.81% improvement in MRR and also Surface Roughness reduce with 5.91%. This finding indicated that the experiments in this study possess excellent repetitiveness and great potential for future reference.

CHAPTER-6

MATHEMATICAL MODELLING

6.1 INTRODUCTION TO REGRESSION ANALYSIS

The term multiple *regression* literally means stepping back toward the average. It was use by British mathematician Sir Francis Galton .Regression analysis is a mathematical measure of the average relationship between two or more variables in terms of the original units of the data. In regression analysis there are two types of variables. The value whose value is influenced or is to be predicted is called *dependent variable* and the variable which influences the values or is to be used for prediction is called *independent variable.* Regression analysis can be done in two ways;

- **Bivariate regression**
- **Multiple regression**

6.1.1 Bivariate Regression:

Two variables X and Y may be related to each other or inexactly. In physical sciences, variables frequently have an exact relationship to each other. The simplest relationship can be expressed by

Y=a+bX

Where the values of the coefficient, **a** and **b,** determine respectively the precise height and steepness of the line. Thus coefficient *a* represent to as the *intercept* or constant, and coefficient *b* referred to as the *slope.*

In contrast, relationship between variables in social sciences is almost always inexact. The equation for a linear relationship between two social science variables would be written as:

Y=a+bX+e

Where *e* represents the presence of error

6.1.2 The least Squares Principle

In postulating relationship among social science variables, we commonly assume linearity. Of course this assumption is not always correct. Least square principle tells us or identified best line which can fit the model for example. The question arises out of all possible line we should choose. From the scatter plot we will calculated prediction error is calculated as:

Prediction error = observed error - predicted

Summing the prediction error for all observation would yield a total prediction error (TPE).

$$b = \frac{\Sigma(X_i - \bar{X})(Y_i - \bar{Y})}{\Sigma(X_i - \bar{X})^2}$$

$$a = \bar{Y} - b\bar{X}$$

These values of a and b are our least square estimates. As we know **Multiple Regression Analysis is** use when more than two parameters are used .in my thesis there are 4 parameters so I will consider multiple regression analysis. In multiple regressions analysis linear equation is given by:

$$y = a + bx_1 + CX_2 + \cdots NX_3$$

Where b, c etc are called partial slope .Some terms which are considered in multiple regressions are discussed below:

6.1.3 Residual

The difference between an observed value (y) and its corresponding fitted value (ŷ) is called residual. Residual values are especially useful in regression and ANOVA procedures because they indicate the extent to which a model accounts for the variation in the observed data.

6.1.4 Sampling Error

When estimating a population parameter from a sample it is important not only to derive a specific value but also estimate the effect of the sampling error on the estimate. To accomplish this it is necessary to consider the concept of a sampling distribution for a regression coefficient.

This could be easily understood as the distribution of estimates of the regression coefficient that would be result if sample of given size were drawn repeatedly from the population and coefficient calculated from each sample .Because coefficient estimated from random samples will deviate from populations values by varying amounts, the estimates , the estimates of the coefficient from a series of random samples of population will not be identical but instead will distribute themselves around a mean . the estimated standard deviation of the sampling distribution of a regression coefficients is known as a *standard error* and is denoted by '*s'*.

6.1.5 Coefficient of Determination R^2

This is called ***coefficient of determination*** indicates explanatory power of any regression model. Its value lies between +1 and 0. It can also been shown that R –sq is the correlation between actual and predicted value. It will reach maximum value when dependent variable is perfectly predicted by regression equation.

6.1.6 Multicollinearity

Multicollinearity means that none of that independent variable or linear variable is perfectly correlated with another independent variable or linear combination of other independent variable .In multiple regression if there is collinearity among variables , then regression surface not even define (because in multiple regression instead of two plane we will consider multiple plain) as there are infinite number of surface that fit the observation equally well and there fore it is impossible to drive unique estimates of the intercepts and partial slope coefficient for the regression

6.2 FIRST ORDER LINEAR MODEL FOR MRR

With the help of Minitab 15 Software, I developed first order linear model and ANOVA Table.

The regression equation for MRR is

MRR (g/sec) = 0.452 - 0.0205 Gas Pressure (Bar) + 0.000167 current (A) + 0.000621 cutting speed (mm/min) + 0.0194 arc gap (mm)

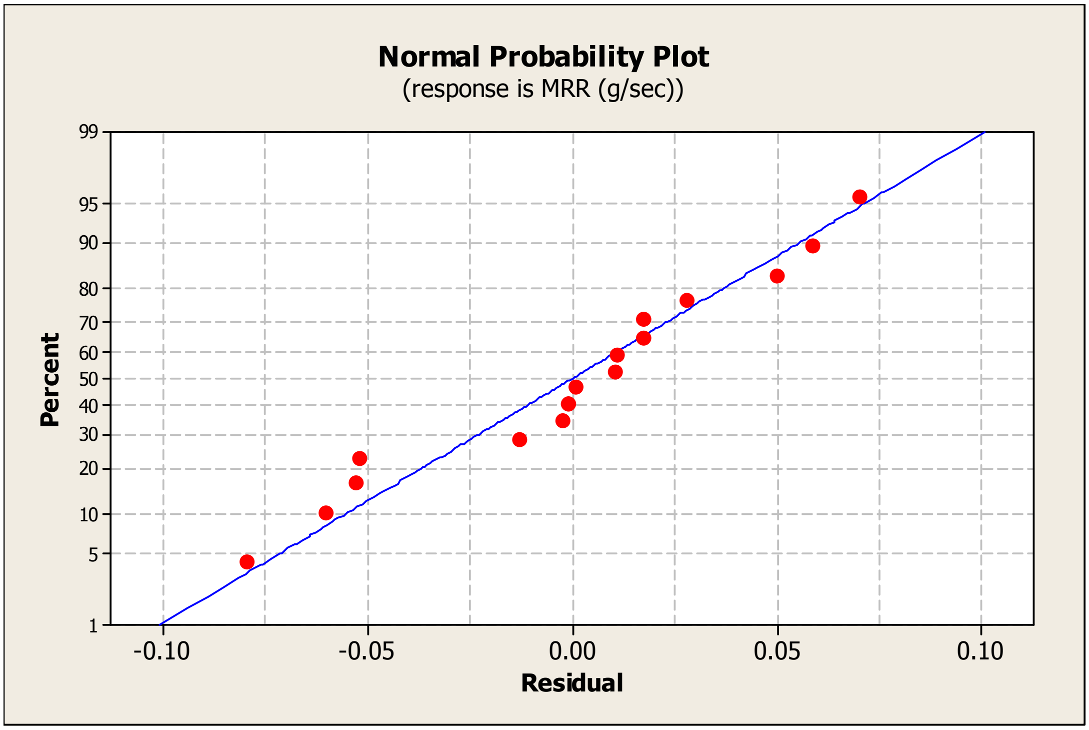
S = 0.0505298 **R-Sq = 71.2%** **R-Sq(adj) = 60.8%**

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	0.069590	0.017397	6.81	0.005
Residual Error	11	0.028086	0.002553		
Total	15	0.097676	0.097676		

Model Adequacy Check: The P- value of Regression equation (0.050) indicates that the regression model is significant. The coefficient of determination (R2) which indicates the goodness of fit for the model so the value of R2 =71.2% which indicate the high significance of the model.

Graph 6.1 Normal Probability Plot for Residuals of MRR



This graph indicates that the residual follows a straight line and there are no unusual patterns or outliers. As a result, the assumptions regarding the residual were not violated and the residuals are normally distributed.

6.3 FIRST ORDER LINEAR MODEL FOR SURFACE ROUGHNESS

The regression equation for SR (Ra) is:

SR (Ra) = 4.91 - 0.430 Gas Pressure (Bar) - 0.00897 current (A) + 0.00445 cutting speed (mm/min) + 0.0183 arc gap (mm)

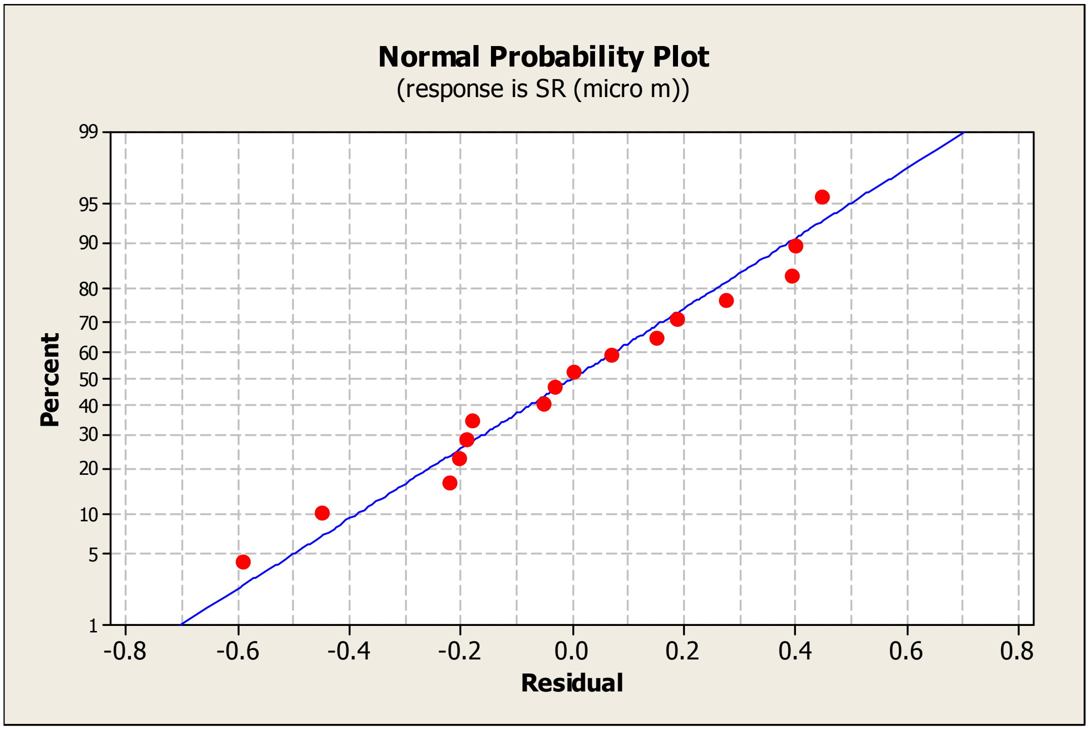
S = 0.352974 **R-Sq = 77.5%** **R-Sq(adj) = 69.3%**

Analysis of Variance

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	4	4.7189	1.1797	9.47	0.001
Residual Error	11	1.3705	0.1246		
Total	15	6.0894			

Model Adequacy Check: The P- value of Regression equation (0.001) indicates that the regression model is significant. The coefficient of determination (R2) which indicates the goodness of fit for the model so the value of R2 =77.5% which indicate the high significance of the model.

Graph 6.2Normal Probability Plot for Residuals of Surface Roughness (Ra)



This graph indicates that the residual follows a straight line and there are no unusual patterns or outliers. As a result, the assumptions regarding the residual were not violated and the residuals are normally distributed.

CHAPTER 7

RESULT, CONCLUSION AND FUTURE SCOPE

7.1 SUMMARY

Objective of this study is to find out optimal condition of Plasma Arc Cutting Machine for maximizing MRR and minimizing Surface Roughness (Ra). For this 16 specimens of Stainless Steel material were prepared which were easily and cheaply available in the scrap yard of Fabrication Division of BHEL, Bhopal. The mechanical properties of Stainless Steel (316L) are given in appendix B .Machining process is carried out on Plasma Arc Cutting Machine number B/0/2163 which is available in the Fabrication Division of BHEL, Bhopal. I considered MRR and Surface Roughness (Ra) as two most important outputs.

As per literature review Gas Pressure, Current Flow Rate, Cutting Speed and Arc Gap were considered as most important parameters. In order to perform minimum experiments Taguchi method has been employed. For this L16 orthogonal array is considered .Experiment results and various response graph for MRR and SR (Ra) were obtained and there optimum value were also considered.

In chapter 6 mathematical modeling were done .For this I consider **regression analysis .** Mathematical equation both for MRR and SR (Ra)were obtained by regression analysis.

7.2 RESULTS

The Optimum levels of parameters for **maximizing MRR** are A1 B2 C2 D2 i. e.

Gas Pressure: 5 Bar

Current: 150 A

Cutting Speed: 600 mm/min

Arc Gap: 4mm

The optimum levels of parameters for **minimizing Surface Roughness (Ra)** are A2 B2 C1 D1 i. e.

Gas Pressure: 6 Bar

Current: 150 A

Cutting Speed: 400 mm/min

Arc Gap: 2 mm

After performing experiment as per given optimum levels for MRR and SR following results obtained:

Table 7.1 Results Before and After Optimisation

MRR (g/sec)	**Predicted value of A1B2C2D2 = 0.8264**	**Experimental result of A1B2C2D2=0.8331**	**Percentage = 0.81%**
Surface Roughness (μm)	**Predicted value of A2B2C1D1 = 2.8006**	**Experimental result of A2B2C1D1=2.635**	**Percentage = 5.91%**

So we can say that there is 0.81% improvement in MRR and also Surface Roughness reduce with 5.91%. This finding indicated that the experiments in this study possess excellent repetitiveness and great potential for future reference.

7.3 DISCUSSION

- As per analysis, the significant parameter for optimum MRR calculation is Cutting Speed and the significant parameters for Surface Roughness calculation are Gas Pressure, Current and Cutting Speed.
- Although some parameters are not significant but we able to improve MRR and Surface Roughness.
- As per regression analysis the mathematical models of first order for MRR and SR (Ra) are showing significant results.
- Table 4.2 shows the analysis result for MRR. In this case speed is significant model term. In the model term graph for speed is increase for MRR. It can determined that when the level of the factor increased, the MRR response also increase significantly. Values greater than 0.1000 indicate the model terms are not significant. Speed factor are most important to measured maximize Metal Removal Rate (MRR) for Stainless Steel (316L) Material. Another factors influence for MRR is equipment system and environments. The equipment systems, torch vibration, nozzle gag (blocking air), and working table area are each factors influence MRR.
- Table 4.7 shows the ANOVA result for Ra. P values less than 0.0500 indicate model terms are significant. In this case there are Gas Pressure, Current and Cutting Speed are significant terms. In the main effect term graph for pressure and current are increased for minimizing Ra, and the speed is decreased for minimizing Ra.

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7.4 CONCLUSION

This thesis has presented an application of the Taguchi method to the optimization of the machining parameters of Plasma Arc Cutting Machine. As shown in this study, the Taguchi method provides a systematic and efficient methodology for determining optimal parameters with far less work than would be required for most optimization techniques. The confirmation experiments were conducted to verify the optimal parameters. It has been shown that Material Removal Rate (MRR) and Surface Roughness (Ra) can be significantly improved in the Plasma Arc Cutting process using the optimum level of parameters.

Plasma Arc Cutting Machine is widely utilized in BHEL, Bhopal to cut materials such as Stainless Steel and Nickel-Base Alloys. This is the basis work where Plasma Arc Cutting was utilized to perform the material removal process at finishing stage. The Plasma Arc Cutting (PAC) machining of Stainless Steel (316L) has been performed with the application of combination with design of experiment (DOE).The PAC parameters studied were how to have setting for the parameter such as Gas Pressure, Current flow, Cutting Speed and Arc gap of machine.

From ANOVA of MRR we can say that some parameters are not making any significant effect .This is because we must take large number of observations either by considering L27 0r L32 orthogonal array with 3 level designs.

Mathematical equation for MRR of first order is of R-sq of 71.2% and for Surface Roughness (Ra) is of R-sq 77.5% which is acceptable.

7.5 SCOPE OF FUTURE WORK

Based on result and discussion summary, this project had archive it main objective but an improvement still can done to improve more on the Metal Removal Rate (MRR) and Surface Roughness (Ra) of parts by features. Some of the suggestions to improve the result include the replication of the model which can reduce the variations of the data and increase the reliability of the data.

Based on this work many improvements can be made and the scope can also be widened. Following are suggestion for future work:

- Using Plasma Arc Cutting system, add the parameter such as Kerf, Voltage, angle, material dimension, and change advance material such as brass and bronze then compare the result obtained.

- Using other methodology in the same material of study to compare the results obtained such as Response Surface Methodology, Grey Relational Analysis, and Genetic Algorithm etc.

- Study for manual calculation for other method in DOE to improve knowledge and skills.

- No interaction is considered so we can consider interaction by applying L27 or L32 with 3-level design this will improve optimum condition as compare to L16 considered in this work.

- Also side clearance and thermal effect on material and work piece like Heat Affected Zone (HAZ) can also be considered to study the effect on properties of work piece.

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